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A Novel Position Sensorless Speed Control Scheme for Permanent Magnet Synchronous Motor Drives

원태현 · 박한웅* · 송달섭 · 김문수 · 이만형**
동의공업대학 · 해군사관학교* · 부산대학교**
Tae-Hyun Won · Han-Woong Park* · Dall-Sup Song · MoonSoo Kim · Man-Hyung Lee**
Dongeui Institute of Technology · Korea Naval Academy* · Pusan National University**

Abstract - *A sensorless control strategy for permanent magnet synchronous motors is presented in this paper. A speed control scheme based on the measurement and observation of stator current, voltage, and flux vector is proposed. Two phase voltages and two stator currents are measured and processed in discrete form in DSP. The rotor position and speed are estimated through the stator flux and its derivative estimation. Flux and its derivative are calculated in the stationary reference frame and used to estimate the speed and position. The rotor position angle is then used in a microcontroller to produce the appropriate stator current command signals for the hysteresis current controller of the inverter. The closed-loop speed control has been shown to be effective from standstill to rated speed. Moreover, a flux drift problem caused by the integration can be eliminated so that a stable sensorless starting and running operation can be achieved. Computer simulation and experimental results are presented to demonstrate the effectiveness of the proposed scheme.*

I. INTRODUCTION

Permanent magnet synchronous motors (PMSM) are receiving increased attention for drive applications because of their high torque to inertia ratio, superior power density, and high efficiency. In most variable speed drive systems, some types of shaft position sensor such as an optical shaft position encoder or resolver is fitted to provide a signal that is used to maintain an appropriate space angle between the stator and rotor field of the motor. In many industrial installations, the presence of this shaft sensor may substantially reduce the overall ruggedness of the drive. In others, it may add significantly to the drive cost.

Because of these drawbacks, shaft position sensor elimination techniques have received attention within the last decade. Position sensorless control of PMSMs has been studied by many researchers, and a number of schemes have been suggested [1-6]. However, many of the methods work for some PMSMs, but not all.

This paper describes an alternative simple method of position estimation implemented in real time and in closed loop for PMSMs, and gives results in sinusoidal phase current excitation of the drive. Stator voltage and current signals are used to construct a flux linkage position signal through which the phase angle of the stator current can be controlled. The rotor position and speed are estimated through the stator flux and its derivative estimation. They are calculated in the stationary reference frame and used to estimate the speed and position. The closed-loop speed control has been shown to be effective from standstill to rated speed. Moreover, a flux drift problem caused by the integration can be eliminated so that a stable sensorless starting and running operation can be achieved. Test results are presented to demonstrate the feasibility of the proposed scheme.

Ⅱ. Proposed Sensorless Algorithm

A. SYSTEM CONFIGURATIONS

The control scheme proposed in this paper for the sensorless PM synchronous motor drive is shown in Fig. 1. It is based on the vector control principle arranged in the d-q rotating frame aligned with the rotor flux. The motor currents in the two-phase stator reference frame α-β are calculated by the measurement of two actual phase currents and voltages and by applying three-phase to α-β transformation. Hence, the d-q components are obtained using the estimated rotor position and speed. The quadrature i_q component is controlled to the reference value given by the speed controller, whilst the direct i_d component is controlled at zero in order to minimize the current vs. torque ratio of the motor.

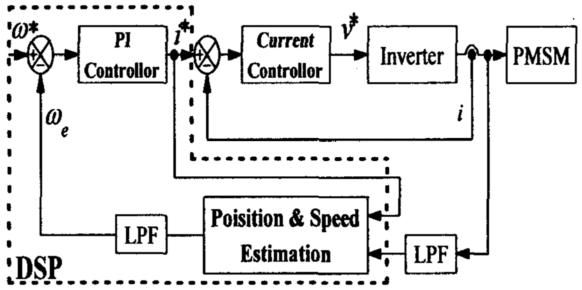


Fig. 1. Block diagram of the proposed sensorless control system

An outer speed control loop completes the scheme. The controller used is a standard PI regulator. The rotor position estimator is arranged in the two-phase fixed -reference frame. The rotor position is calculated by means of an estimation of the flux and its derivative, using the instantaneous values of the motor phase currents and terminal voltages.

B. PROPOSED ALGORITHM

The implementation of the control scheme in Fig. 1 by means of the detection of the flux-linkage and its derivative components can be split into two different actions:

1) the evaluation of the transformation matrix, needed to perform the vector control
2) the estimation of the speed needed to perform the speed control.

As known, the transformation matrix of *a-b-c* to α-β reference frame is defined by

$$C_1 = \sqrt{\frac{2}{3}}\begin{bmatrix}1 & -0.5 & -0.5\\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2}\end{bmatrix} \tag{1}$$

Using the matrix, the flux linkages in the α-β frame can be expressed as follows:

$$\lambda_s = \lambda_\alpha + j\lambda_\beta \tag{2}$$

$$|\lambda_s| = \sqrt{\lambda_\alpha^2 + \lambda_\beta^2} \tag{3}$$

Since the motor has a uniform inductance around the airgap, $L_\alpha = L_\beta = L$. Therefore, λ_α and λ_β can be written as

$$\lambda_\alpha = L_\alpha i_\alpha + \lambda_{m\alpha} = Li_\alpha + \lambda_{m\alpha} \tag{4}$$

$$\lambda_\beta = L_\beta i_\beta + \lambda_{m\beta} = Li_\beta + \lambda_{m\beta} \tag{5}$$

where $\lambda_{m\alpha}$ and $\lambda_{m\beta}$ represent the flux linkages by the rotor magnet. The stator flux linkages can also be written in a trigonometric form as

$$\lambda_\alpha = \sqrt{\frac{3}{2}}\,|\lambda_s|\,\cos(\theta_e - \theta_1) \tag{6}$$

$$\lambda_\beta = \sqrt{\frac{3}{2}}\,|\lambda_s|\,\sin(\theta_e - \theta_1) \tag{7}$$

Therefore, the derivatives of the flux linkages can be obtained as follows:

$$\frac{d\lambda_\alpha}{dt} = -\sqrt{\frac{3}{2}}\,\omega_e|\lambda_s|\,\sin(\theta_e - \theta_1) \tag{8}$$

$$\frac{d\lambda_\beta}{dt} = \sqrt{\frac{3}{2}}\,\omega_e|\lambda_s|\,\cos(\theta_e - \theta_1) \tag{9}$$

Substituting (6) and (7) into (8) and (9), following equations are obtained.

$$\frac{d\lambda_\alpha}{dt} = -\omega_e\lambda_\beta \tag{10}$$

$$\frac{d\lambda_\beta}{dt} = \omega_e\lambda_\alpha \tag{11}$$

Eqs. (10) and (11) imply that the instantaneous motor speed can be estimated by obtaining the flux linkages and their derivatives. The evaluation of the flux linkages and their derivatives is made by substituting (6) and (7) into (8) and (9), and following equations are obtained.

$$\hat{\lambda}_\alpha = L i_\alpha + \hat{\lambda}_{m\alpha}(\hat{\theta}_e) \tag{12}$$

$$\hat{\lambda}_\beta = L i_\beta + \hat{\lambda}_{m\beta}(\hat{\theta}_e) \tag{13}$$

$$\frac{d\hat{\lambda}_\alpha}{dt} = v_\alpha - R\,i_\alpha \tag{14}$$

$$\frac{d\hat{\lambda}_\beta}{dt} = v_\beta - R\,i_\beta \tag{15}$$

Therefore, the motor speed and position can be estimated as follows:

$$\hat{\omega}_e = \frac{\sqrt{\left(\frac{d\hat{\lambda}_\alpha}{dt}\right)^2 + \left(\frac{d\hat{\lambda}_\beta}{dt}\right)^2}}{\sqrt{\hat{\lambda}_\alpha^2 + \hat{\lambda}_\beta^2}} \tag{16}$$

$$\hat{\theta}_e = \hat{\theta}_e(0) + \int \hat{\omega}_e\,dt \tag{17}$$

The mechanical dynamic equations of the motor and load are

$$\theta_m = \int \omega_m \bullet dt \tag{18}$$

$$\omega_m = \frac{2}{P}\omega_e \tag{19}$$

$$T_e = TL + J\frac{d\omega_m}{dt} + B\omega_m \tag{20}$$

From Eq. (16) and (17), The speed and position sensorless algorithm is very simple and clear, and can be easily implemented by a microcontroller. Moreover, The sensorless algorithm does not incorporate a mathematical integration. This means that the drift or offset which arise from the DC components caused by the integration can be eliminated, and therefore the accuracy of both the position and speed calculation can be greatly improved.

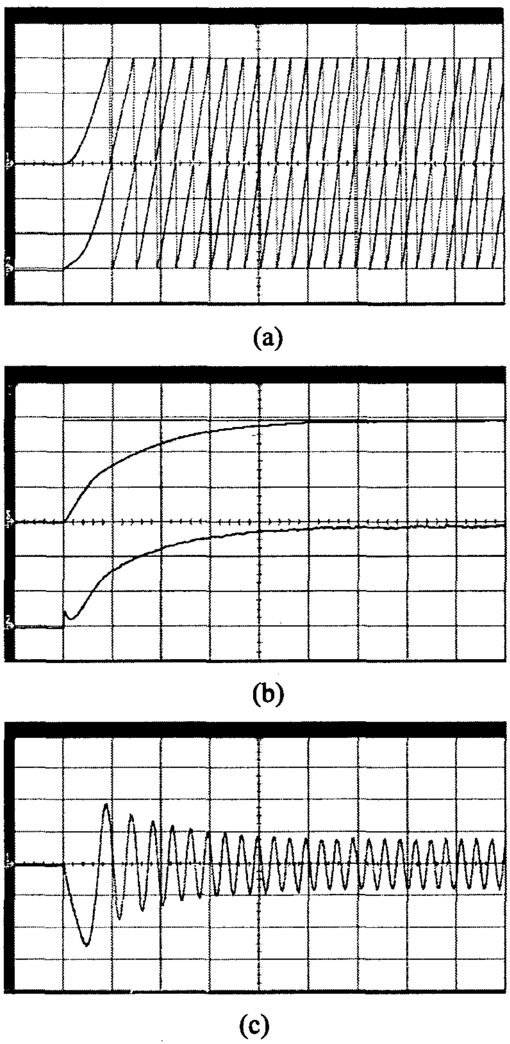
Ⅲ. Experiential Results

The proposed algorithm has been tested and implemented in a general purpose TMS320F240 digital signal processor (DSP). The DSP is connected to the peripheral I/O board. Current regulation is executed every 100 s and speed control loop is executed every 200 s. The specifications and per phase parameters of the machine tested are listed in Table 1.

Table. 1. The measured motor parameters

Winding resistance	1.6 [Ω]
Winding inductance	13.4 [mH]
Max. value Of the flux linkage	0.288 [Wb.t]
Number of poles	6
Rated current	6.0 [A]
Rated Speed	1,200 [rpm]

The motor is star connected internally, and the line currents are measured with current transducers in order to track the reference phase current. For the estimation of the speed and position, the reference phase currents and the measured phase voltages are used. The phase voltages are measured by the potentiometer via a appropriate filter to alleviate the high frequency harmonic components. Since the low-pass filter implemented in the motor terminals can influence the magnitude and angle of the phase voltages, it is important to design a filter cutoff frequency carefully. Moreover, since the motor speed is estimated from the stator voltages and reference phase currents, the high frequency noises are included in the estimated speed. Therefore, Another filter is required to reduce noises. This is done in a digital form within the DSP.

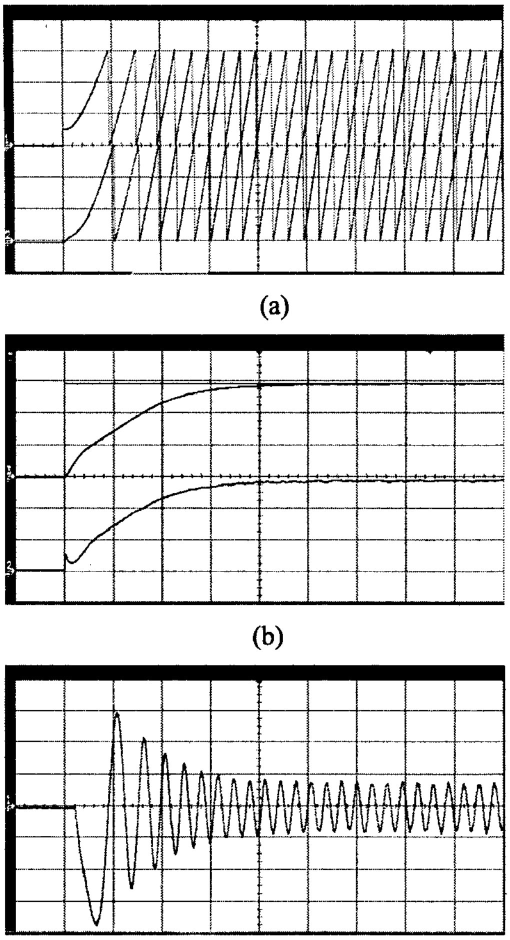

(a)

(b)

(c)

Fig. 2. Startup response from standstill. (a) Measured and estimated rotor position (radians). (b) Measured and estimated rotor speed (rpm). (c) Phase current waveform.

Fig. 2 shows the startup performance of the PMSM from standstill to the command speed of 100 rpm that is the rated speed. The load torque of 3 Nm is applied to the PMSM from starting, and the actual and estimated initial positions are assumed to be identical. From the actual (solid) and estimated (dotted) position traces in the Fig. 2(a) and (b), it is clearly verified that the proposed position sensorless control algorithm has a high performance position estimation capability, and a good speed regulation ability under full speed operating condition.

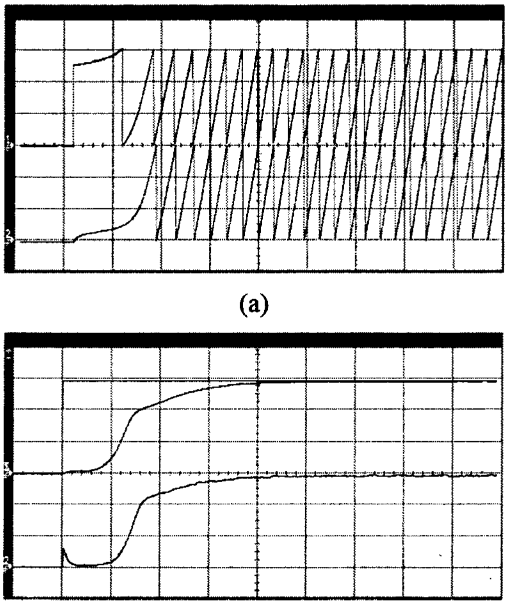


(a)

(b)

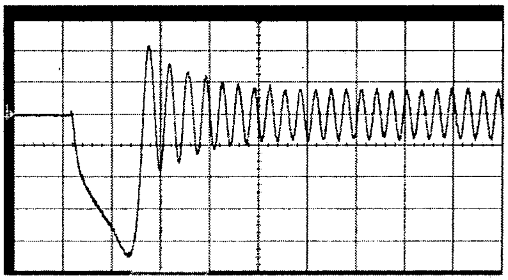
(c)

Fig. 3. Startup from standstill at 60° . (a) Measured and estimated rotor position(radians). (b) Measured and estimated rotor speed (rpm). (c) Phase current waveform.



(a)

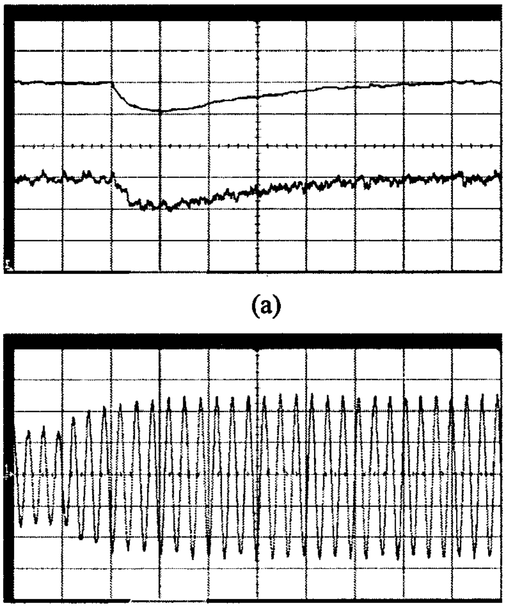
(b)



(c)

Fig. 4. Startup from standstill at 300° . (a) Measured and estimated rotor position(radians). (b) Measured and estimated rotor speed (rpm). (c) Phase current waveform.

Another starting capability of the proposed sensorless algorithm is depicted in Fig. 3. As shown in the test results, even if the initial angular difference between the actual and estimated rotor positions is given by 350o electrical degree, the stable starting performance can be obtained in the case of 3 Nm load condition. The spike in the estimation speed during startup is caused by the large angular difference, and the actual speed follows up the reference speed within 0.02 s. Therefore, considering the ordinary load characteristics where the load torque tends to increase according to the machine speed, the proposed algorithm can be a good alternative.



(a)

(b)

Fig. 5. Response of the proposed sensorless drive system when load torque is varied from 3 to 5 Nm. (a) Measured and estimated rotor speed (rpm). (b) Phase current waveform.

The step response of the load torque variation maintaining the reference speed as 100 rpm is shown in

Fig. 4. The load torque is changed from 3 to 5 Nm. The sudden change of the load torque causes a dip in speed, but the speed controller restores the motor speed to its reference value within 0.3 s. It is noteworthy that the proposed position sensorless controller can still estimate the actual position and speed, and is able to track the dip in speed. The phase current is also presented in Fig. 4(c).

From these test results, the proposed observer shows a good performance and the high degree of robustness to the position and speed error along with PI controller handles changes in speed or load torque satisfactorily.

IV. CONCLUSIONS

A simple and stable position sensorless control strategy for permanent magnet synchronous motors was presented in this paper. A speed control scheme was based on the measurement and observation of stator current, voltage, and flux vector. The rotor position and speed were estimated through the stator flux and its derivative estimation. Flux and its derivative were calculated in the stationary reference frame and used to estimate the speed and position. The closed-loop speed control has been shown to be effective from standstill to rated speed. Moreover, a flux drift problem caused by the integration could be eliminated so that a stable sensorless starting and running operations were achieved. Computer simulation and experimental results were presented to demonstrate the feasibility of the proposed position sensorless algorithm.

V. REFERENCES

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